Progress In The Development of Buried Minehunting Systems

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Abstract - **In FY 2002, the Office of Naval Research (ONR) initiated a project to provide a deliberate capability for hunting buried sea mines. The objectives and approaches for this buried minehunting (BMH) project and the sensor technologies being pursued have been reported [1]. In this paper, we will describe progress and current status of this project, including developments in sensors, platforms, system concepts, and testing. Discussion of relevant tests that have been conducted for individual sensors and sensor combinations will be included. Future plans to test and demonstrate these technologies and concepts are discussed.**

I. INTRODUCTION

Side-looking and ahead-looking sonars are used in minehunting search-classify-map (SCM) operations for the detection, classification, and localization (DCL) of proud sea mines. Either diver observation or optical identification in a reacquisition (RI) phase is commonly used to identify proud sea mines. The DCL of buried sea mines, especially in the shallower waters, poises significant technical challenges. For the purposes of this paper, we will consider a mine to be buried if 75% or more of its volume is covered with sediment. Conventional sonars operating at higher frequencies may not provide effective bottom penetration to classify buried mines. Moreover the identification of buried sea mines in the conventional sense is fundamentally problematic.

A range of new sensing technologies and sensor-fusion approaches are needed to provide a robust capability to address this problem. In particular, prototypes of synthetic aperture sonars (SAS) using low frequency, broadband signals for imaging and those using very low frequency (VLF) signals to discriminate target acoustic color are being evaluated for the SCM of buried mines.

An interesting challenge for BMH is the development of concepts for "reacquisition and identification" ("RI") of buried mines acceptable to the Fleet in the sense that optical identification is now used against proud targets. Data fusion from an appropriate set of sensors operating in a relatively close range to provide a complementary look at a SCM contact is being pursued to increase the confidence that a target classified as a mine in an initial SCM operation is, in fact, a mine. The goal of this approach is to obtain statistical confidence high enough that the fleet is willing to declare it a mine. Prototypes of acoustic down-looking sonars, magnetic sensors, and active electromagnetic sensors are candidates for "RI" from the smaller UUVs. Because a high percentage of buried mines may not be completely buried for some missions of interest, high resolution, imaging electro-optic or acoustic sensors may also be considered for "RI".

The appropriate choice of a sensor suite will depend on the region in which the hunting operations are being conducted and on the environmental conditions at the time of these operations. Such factors as bottom type and variability, clutter, biologic structures, water depth, water turbidity and layering, sea state, and water currents will impact the effectiveness of different system approaches. One can expect that a different sensor suite, likely with a wider range of sensor types, will be needed to hunt robustly in harbors with muddy sediments and with significant man-made clutter than would be required to hunt along pristine, isolated coastlines with sandy bottoms.

Sea minehunting has been typically conducted using systems towed from surface craft or helicopters. One major step taken to improve these capabilities is the introduction of relatively small unmanned underwater vehicles (UUVs) dedicated to the demonstration of new mine countermeasure sensor technologies. UUVs currently being pursued for this project are described in Section II. Integration of these sensor technologies into relatively small SCM and "RI" UUVs presents significant challenges. Issues include sensor size and special packaging considerations, power, vehicle noise, and hydrodynamic stability. General issues are described in Section II. Section III describes candidate system prototypes for SCM operations while candidate sensors for RI operations are discussed in Section IV. Issues specific to any single sensor type are discussed in the relevant section pertaining to that sensor. Section V summaries the salient points of this paper.

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II. UNMANNED UNDERWATER VEHICLES FOR BMH

The basic concept being pursued under this BMH project involves one class of UUVs carrying sonars capable of long-range target SCM and a second class of UUVs carrying additional acoustic and non-acoustic sensors to get a closer look at the SCM contacts. Two basic classes of UUVs, categorized by 21" and 12-3/4" vehicle outer diameters, are being utilized as the primary platforms for BMH sensor demonstration. The Reliant UUV, modeled after the Battlespace Preparation Autonomous Underwater Vehicle (BPAUV) [2] displayed in Fig. 1, is being used to evaluate several of the SCM sonars, in particular, the broadband (BB) SAS (described below in Section III.A) and the VLF Acoustic-Color Classifier (described below in Section III.B).
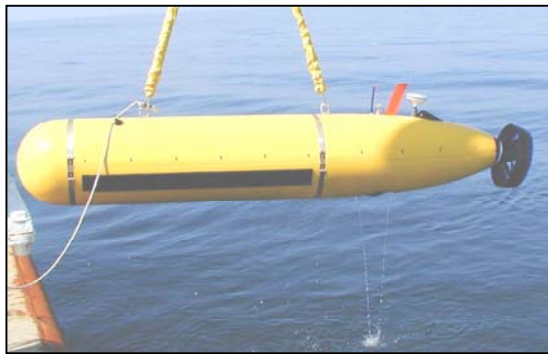

Fig. 1. BPAUV being recovered from the Gulf of Mexico during its intial field trials.

Two 12-3/4" UUVs currently under development for ONR, REMUS 300 [3] and Bluefin12 [4], have been identified for testing and demonstration for BMH. These smaller UUVs are desirable for logistics and ease of deployment. In particular, existing fleet systems can be used to support these new UUVs because 12-3/4" is one standard diameter for naval vehicles. The REMUS 300 has been identified to test the Small Synthetic Aperture Minehunter (SSAM) described in Section III.A. The Bluefin12 has been identified to test the Bottom Object Scanning Sonar (BOSS) (described in Section IV.A) and the range of electromagnetic sensors currently under development (described in Sections IV.B-D). In one concept under consideration, the BOSS and several non-acoustic sensors would be fused together for enhanced "RI". Artist conceptions for these vehicles are depicted in Figs 2 and 3.

To be useful for minehunting missions, these vehicles must provide an environment for effective sensing and provide both endurance and navigational accuracy. Physical and operational characteristics of BPAUV are described in reference 2. Since the length of a vehicle for effective operation decreases as the diameter decreases, requirements on the 12-3/4" vehicles are more stringent than for larger vehicles such as BPAUV; i.e., physical space for the vehicle subsystems and the sensor packages is more limited. In particular, this factor effectively limits the lengths of the sensor packages to be no greater than 48". The sensor types under consideration with satisfactory capability for the BMH mission can only be miniaturized to a certain extent given the current state of technology. Therefore, this length goal can impose a challenge to the sensor designer. This challenge is compounded for concepts in which two sensors are integrated into a single vehicle. Space availability is also a factor for battery packs. The design engineer must provide approaches to power the vehicle and the sensor packages for cases that may require energy capacities on the order of 5 to 10 kW-hrs. Note that the power requirements for the specialized BMH sensors under development range from 20 up to 100 Watts, values that are substantially higher than for many sensors used for oceanographic survey. Another issue arises with the integration of sensors with sizable external appendages. These sensors will introduce extra drag, which will increase the vehicle power requirements, and may influence vehicle flight stability. Specific challenges associated with the different sensors of interest to the BMH project and approaches to address them will be described in the sections dedicated to the different sensors.

III. SEARCH-CLASSIFY-MAP (SCM) SYSTEM PROTOTYPES

The SCM system prototypes all are based on active acoustic sensing technology, either sonars that image targets (described in Section III.A) or those that detect a target's acoustic spectral properties, i.e. acoustic color (described in Section III.B) [1]. Synthetic aperture techniques are being utilized for each of these sonars to reduce sensor length as compared to the lengths required for real aperture sonars.

In order to support assessment of the SCM prototype systems, the Shallow Water Acoustic Toolset (SWAT) was enhanced to incorporate a bottom penetration capability for one- and two-dimensional arrays configured as either forward-, bottom-, or side-looking imaging sonars. The

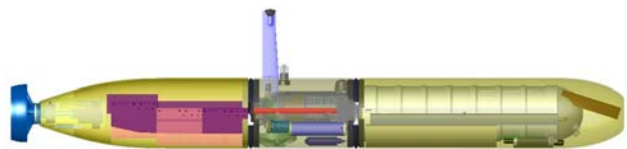Fig 2. Artist conception of preliminary design of REMUS 300.

Fig. 3. Artist conception of preliminary design of Bluefin12.

enhanced model/code provides both for the computation of signal-to-noise ratios (SNRs) and the generation of images for proud and buried targets. The model/code for SNR prediction was validated with buried target detection data collected by the Coastal Systems Station (CSS) in controlled experiments of an acoustic lens sonar prototype [5]. The enhanced SWAT code can also be applied to the RI acoustic sensors. Predictions for one candidate RI sonar are presented in Section IV.A.

A. Low Frequency Imaging Synthetic Aperture Sonars

Two imaging SAS systems are being considered for SCM operations. One system, referred to as SAS21, is a dual frequency system that operates at a high frequency (HF) of 180 kHz and a low frequency (LF) of 20 kHz. This system has a 21" diameter with a length of approximately 36." SAS21 was developed in the 1990's for the acoustic imaging of both proud and buried targets and provides resolutions of 3"x3" at 20 kHz and 1"x1" at 180 kHz. To further improve the performance of SAS21, a broadband low frequency transmitter prototype was developed and integrated with SAS21 (Fig. 4). This sensor combination is referred as BBSAS. The operational bandwidth of the LF portion of the system using the new transmitter has increased from 15-25kHz to 8-55kHz. The BBSAS has been successfully tested onboard CSS's advanced sensor tow vehicle [6].

SAS21 has been assessed against proud and buried targets (cylinders, fluid-loaded spheres, air-backed spheres, etc.). Figs. 5 and 6 depict SAS HF and LF images, respectively. Two images appear in each figure: one image corresponds to a SWAT prediction and the second image refers to an image
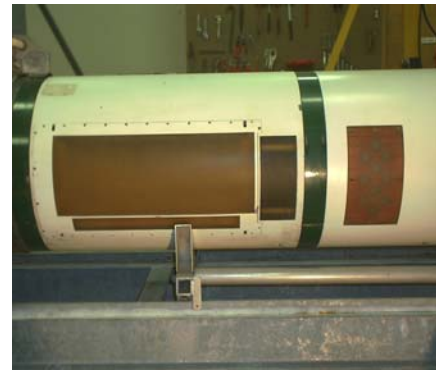
Fig. 4. Photograph of the BBSAS system with SAS21 displayed on the LHS and the BBSAS transmitter on the RHS of the photograph.

synthesized with data collected with the SAS21 integrated into a tow body. Fig. 5 displays the HF image of a cylindrical target sitting on a sandy bottom, while Fig. 6 displays the LF images of a row of buried targets. (These LF images for the buried targets were obtained with the LF subsystem operating in the frequency range of 15-25 kHz and a grazing angle of approximately 50°.) The target size and shape of the SWAT-predicted and the SAS21-synthesized images are in good agreement for both the proud target in Fig. 5 and the buried targets in Fig. 6. The target shadow as displayed for the SWAT-predicted and the SAS21-syntheszed HF image in Fig. 5 are also in good agreement. In addition, the SWAT-predicted and SAS21-measured SNRs levels compared well for both the proud and buried target cases.

Fig. 5. HF SAS image of proud target with SWAT prediction displayed on top and SAS21-synthesized image on bottom.

Fig. 6. LF SAS images of buried targets with SWAT predictions displayed on the right and SAS21-synthesized image on left.

Fig. 7. SAS21 integrated onto Reliant UUV.

Fig. 8. Photograph of the VLF prototype system.

Recently SAS21 was integrated into the Reliant AUV and has undergone its first series of sea tests [7]-[8]. A photograph of this sea-going system is shown in Fig. 7. Future plans call for the integration of BBSAS with Reliant and their subsequent testing.
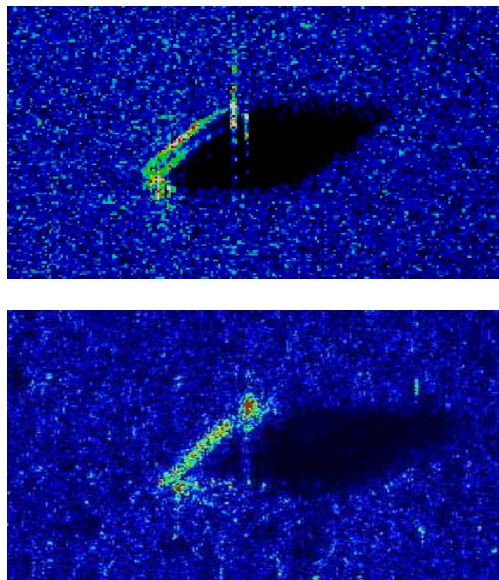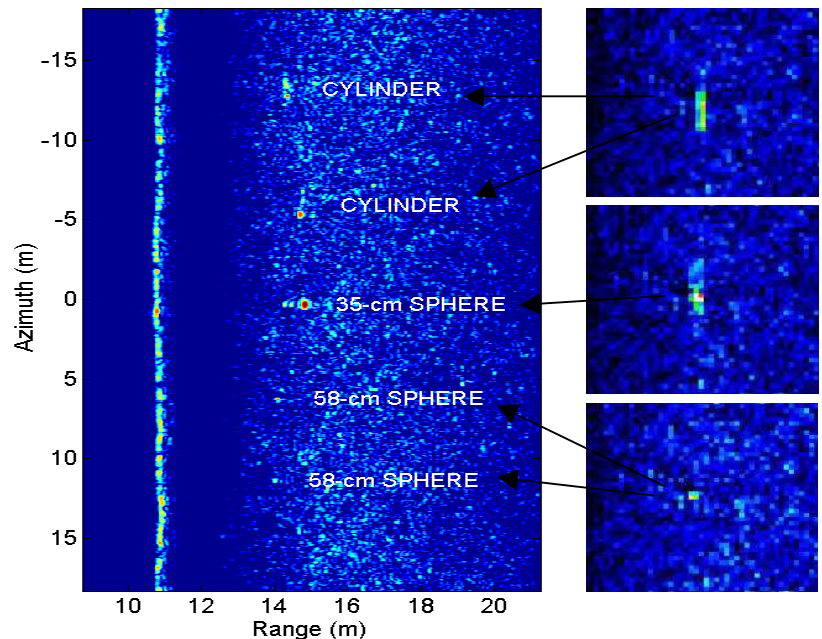
SSAM is the second imaging SAS system. SSAM has the same basic design as SAS21 but has been down-sized to fit into the 12-3/4" UUVs. In particular, it is a dual frequency system operating at 20 and 120 kHz with corresponding resolutions of 3x3" and 1"x1", respectively. It has a 32-cm array giving it a maximum range of 40 meters when operating at 4 knots. Currently there are plans to integrate and test it onboard the REMUS 300 in 2004.

B. Very Low Frequency (VLF) Acoustic-Color Classifier

A VLF sonar approach is also being pursued not for imaging, but to classify both proud bottom and buried mines from their acoustic color; i.e. to discriminate a target by its structural acoustic mechanisms [1]. This frequency response is selected to effectively detect the acoustic color from both proud bottom and buried mines, since the VLF source-signals provide relatively deep penetration into the sea-floor bottom. Furthermore, SAS signal processing is used to enhance SNRs. The current version features a VLF projector and a vertical-array receiver for generating and detecting a broadband signal in the range of 1-8 kHz (Fig. 8). The projector and the receiver are housed in vertical appendages exterior to the sensor's body section. This sensor has been demonstrated from a tow body. Further testing has been initiated with the sensor integrated onboard the Reliant UUV.

IV. REACQUISITON-"IDENTIFICATION" SENSORS

Optical identification, which can provide compelling confirmation that a proud sonar contact is a mine, is obviously not possible for fully buried mines. Hence a major challenge for the BMH project is to develop an effective buried mine confirmation approach in place of optical identification. The use of complementary sensors operating at close range in a reacquisition operational phase will provide an additional classification capability. It is anticipated that an appropriate set of such reacquisition sensors can be selected so that the probabilities of classification obtained against buried targets will be sufficiently high for the operator to efficiently and decisively take further action in the conduct of subsequent mine countermeasures activities, e.g. neutralization. Downward-looking sonars, such as the BOSS system described in Section IV.A, passing over a contact from the SCM sonars will provide a complementary acoustic image of the contact, which is expected to improve the classification of buried mines. Passive magnetic and active electromagnetic (EM) sensors, such as the ones described in Sections IV.B-D, represent additional options to enhance classification. The use of high-fidelity imaging EO and acoustic sensors is discussed in Section IV.E.

A Buried Object Scanning Sonar (BOSS)

BOSS is a low frequency, downward looking sonar [9]. In the context of this project, it is primarily intended for confirmation in reacquisition operations, and it provides complementary target views to those obtained from the side-looking SCM sonars. BOSS employs a separate projector and a receive array. It utilizes near field beamsteering techniques with a planar receive array to provide 3-D focusing and 3-D target imaging as contrasted to the 2-D imaging of side looking sonars. This focusing ability provides high scattering noise rejection, higher resolution for imaging, and multiple-aspect viewing. Both real-time image processing and acoustic-color classification algorithms can be implemented with this system, whereas two distinct sensor types are currently being employed to obtain these complementary perspectives optimally for SCM.
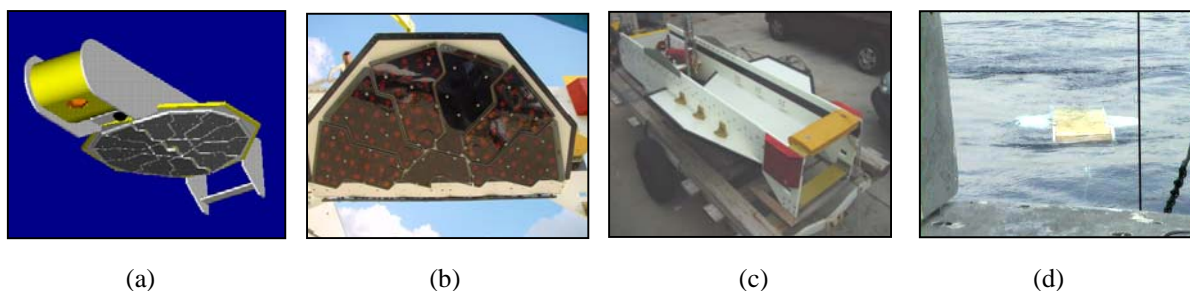
Fig. 9 Second generation of BOSS configured in a tow body: (a) front, bottom view showing the receive array (artist conception), (b) 14 segments of the receive array, (c) rear, top view, and (d) tow body being deployed at sea.

Results from a first-generation feasibility prototype employed in a rail system have been reported [9]. This initial prototype employed a 61-cm long line array of six piston projectors oriented along a centerline and operated in the 5 to 23 kHz frequency range. Sixteen elements were positioned on either side of the projector array to form the receive array (32 total receive elements forming an aperture of approximately 83 cm by 83 cm).

A second generation of BOSS is being developed for demonstration [10]. This version is towed by a surface craft, and it features a 252-element receiver array on a 1.5m disc to provide improved resolution as compared to the initial prototype. A single omni-directional projector is being employed in place of the six-element line projector array used in the first feasibility prototype. Fig. 9 shows this second generation BOSS tow body system.

Use of the disc configuration onboard a small UUV will introduce significant additional drag to the UUV. For this reason, a new concept has been introduced in which the receive array will be integrated into a winged design. In addition, synthetic aperture signal processing will be employed, making it possible to shorten the array along track. A single omni-directional projector will again be utilized. In the proposed design, the receive array will be on two wings (one wing on either side of the UUV) with each wing being about 70 cm in length. Drag is significantly reduced in this configuration. Other challenges, notably vehicle roll stability, are being addressed in the design analysis phase.

The enhanced SWAT computer code is being used to assess the capability of a bottom-looking sonar configured similar to the new-concept BOSS system. Fig. 10 is a SWAT prediction showing the imaging capability of such a configured sonar system. In this test case, the sonar is operating at 7 kHz with a 10 kHz bandwidth. In addition, the sonar is located 3 m above a sandy bottom with each receive array wing tilted upward toward the sea surface at a 45° angle with respect to the horizontal. The test target is a cylinder 2 m in length and 50 cm in diameter that is sitting proud of the bottom and positioned 5 m from the sonar. The SWAT image displayed in the figure has been processed using SAS techniques resulting in a 10-cm by 7.5-cm resolution. This image clearly predicts the appropriate target size and shape.

B. Realtime Tracking Gradiometer (RTG)

The merit of acoustic and magnetic sensor fusion for buried mine detection was first demonstrated in the Magnetic and Acoustic Detection of Mines (MADOM) Advanced Technology Demonstration. A high performance magnetic gradiometer employing helium-cooled superconducting technology was first successfully demonstrated in MADOM. This gradiometer incorporated five independent channels of data, which provides information that has been demonstrated to be valuable for target classification and localization and for clutter rejection. These capabilities significantly exceed that demonstrated by a one-channel magnetometer or a one-channel gradiometer [1], [11].

The Quantum Magnetics' Realtime Tracking Gradiometer (RTG) is a multi-channel tensor gradiometer being developed using fluxgate technology [12]-[13]. It provides sensitivities, and hence detection ranges, that are moderate in comparison to the MADOM superconducting gradiometer. The current version of the RTG was developed and has been demonstrated for hand-held applications such as UXO detection on land. As was the case for the MADOM superconducting gradiometer, the RTG provides five comparable independent channels of information, so that the signal processing already developed and demonstrated in MADOM can be directly applied to the RTG.

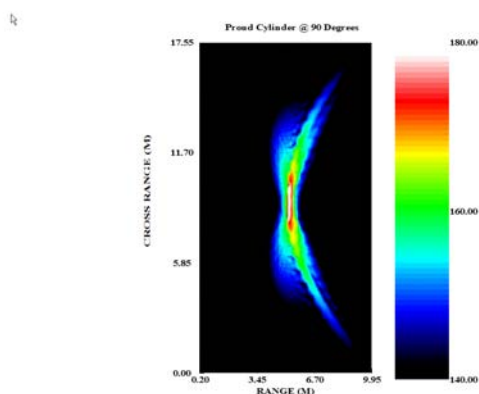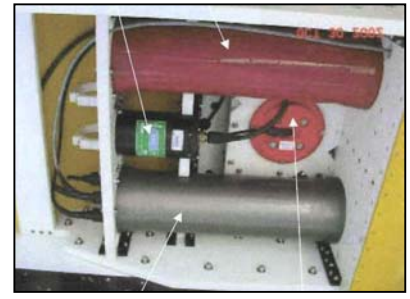Fig. 10. SWAT predicted image of a new-concept BOSS like system. Image synthesized using SAS techniques.

(a)   (b)   (c)

Figure 11. Current version of the Realtime Tracking Gradiometer mounted in the BOSS sled: (a) top view of sensor subsystem integrated into a pressure vessel mounted at the rear of the BOSS sled, (b) back view of the BOSS sled displaying the RTG sensor subsystem, and (c) top view of front end of BOSS sled with the "red" pressure vessel for the RTG electronics subsystem displayed above the "grey" pressure vessel for the BOSS electronics.

Since the magnetic noise generated by electrical subsystems and propulsion units may effectively limit the sensitivity of higher performance sensors, the RTG can be considered as a good compact and affordable candidate for UUV operation. The existing version of the RTG has been used in several land-based tests to establish the effectiveness of magnetic sensors onboard UUVs [14]-[16]. Sensitivities obtained from these tests are essentially at the noise floor of the sensor under ideal "magnetically quiet" conditions. A nominal threshold detection range of 16 m against a 1000lb bomb is predicted for both towed and UUV operations. Sea tests of the existing RTG onboard Reliant are planned to identify any noise issues, which might arise from in-water operation that would not otherwise appear from the land-based testing, e.g. from vehicle corrosion currents.

One interesting sensor-fusion concept under consideration is to integrate the BOSS and RTG sensors onboard a single UUV for "RI" of minelike contacts established in an initial sonar SCM search. In order to explore this concept, the existing RTG has been integrated onboard the BOSS II sled (Fig. 11). Tow tests to demonstrate BOSS/RTG fusion will be conducted in the near future.

Based on the initial land-based test results, a new miniaturized version of the RTG is being developed for unmanned operation onboard the 12-3/4" UUVs. An artist's conception of a design for the RTG mounted into a single UUV body section is displayed in Fig. 12. The design for the new RTG's sensor subsystem will be similar to the designs of its predecessors. In Fig. 12(a), four fluxgate triads are configured in a square arrangement mounted in a vertically-oriented plate. This configuration contrasts to the previous arrangement with three fluxgate triads at the corners of a
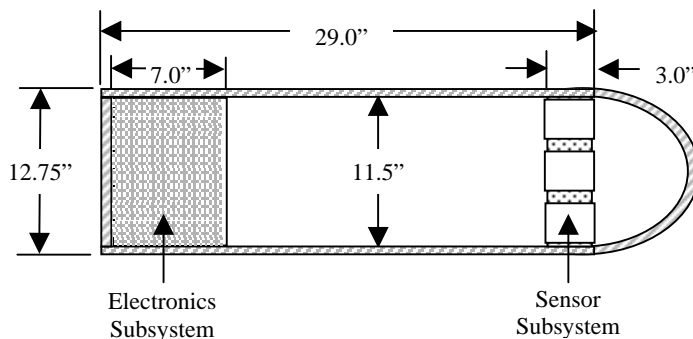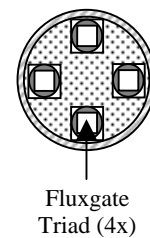
(a)   (b)

Figure 12. One concept of the new RTG configured with both sensor and electronic subsystems in a single modular section for a 12-3/4" UUV: (a) cross-sectional view of body section with the sensor subsystem positioned forward at the nose and with its electronics subsystem positioned aft in the same UUV body section and (b) front-on view of the sensor subsection displaying the four fluxgate triads in the sensor subsystem (three triads with nulling coils under feedback control and a fourth reference triad to drive the feedback). This configuration isolates the sensor subsystem as far away as possible from the magnetic-noise sources from vehicle subsystems in the rear of the vehicle. Note that there is a 19" separation between the sensor and the electronics subsystems as required to mitigate RTG self noise from its own electronics.

triangle operated in a horizontal plane and a fourth triad at the center of the triangle. Five independent tensor-gradient components are synthesized by appropriate subtraction of signals from the magnetometers. A feedback approach is implemented in which field-generating coils, surrounding the three primary triads, null out the Earth's magnetic field at the triads. The fourth fluxgate triad, without a surrounding coil, acts as a reference to set the appropriate level of the nulling fields at the other three triads. This feedback approach reduces dynamic range requirements that would otherwise limit gradient sensitivity when two vector magnetometers are rotated in the Earth's magnetic field. The gradient baseline is reduced down to 6.5", from 12" in the earlier version, in order to fit into the smaller UUVs.

The electronics subsystem for this version is similar in design to the earlier versions, except that there is an emphasis on miniaturization and the subsystem includes a computer for automated sensor operation and autonomous signal processing. In addition, magnetic-signature reduction and magnetic-noise compensation are important factors being designed into the Bluefin12 UUV.

C. Laser Scalar Gradiometer (LSG)

The Polatomic P-2000 is a scalar magnetic sensor based on the electron-spin resonance (ESR) properties of helium-4 gas in accordance with the Zeeman effect, very similar in concept to the US Navy's AN/ASQ-81 and -208 [17]. The P-2000 has attained increased sensitivity by the use of a laser in place of incoherent light for optical pumping. It has been configured for high performance operation in dual modes as either a one-channel magnetometer or a one-channel gradiometer. The underlying physics and sensor operating principles necessary to appreciate technical comments in this section are described in Ref. 18.

Figure 13. P-2000 configured in front of BPAUV for experiments simulating UUV operations.

The P-2000 has been evaluated for the minehunting application under simulated tow and UUV operations [19]. The configuration used for UUV testing is displayed in Fig. 13. Nominal threshold detection range of 34 and 28 m against a 1000lb bomb have been predicted for towed and BPAUV/Reliant UUV operations, respectively.

The Laser Scalar Gradiometer (LSG) is an enhanced version of the P-2000 currently under development for the BMH Project. It is being designed to operate on the 12-3/4" UUVs. An artist's conception of the LSG is displayed in Fig. 14. It employs a multi-channel sensor configuration to provide classification and localization capabilities comparable to that of the five-channel tensor gradiometers described above. Four helium sense cells are configured in a volume-filling arrangement to measure four independent channels of information: the scalar field magnitude and admixtures of the three components of the scalar-field gradient vector from which the scalar-gradient vector can be calculated algebraically.

(a)   (b)
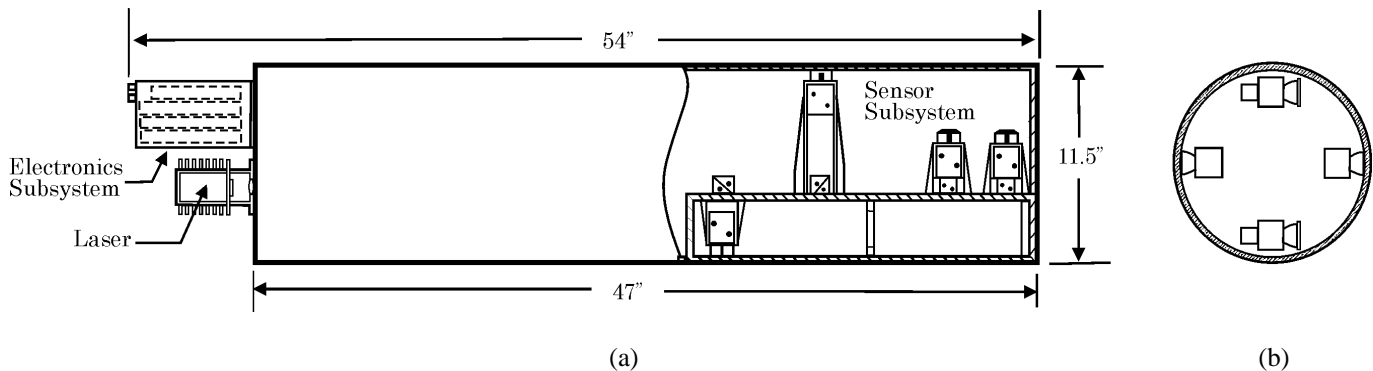
Figure 14. Artist's concept of the design for the LSG: (a) cross-sectional view of vehicle body section with the sensor subsystem mounted rigidly at one end of a support tube to be positioned forward at the nose and its electronics subsystem positioned aft in the same section and (b) front-on view of the sensor subsection displaying the four helium sense cells in the sensor subsystem. Note that there is a 32" separation between the sensor and the electronics subsystems to mitigate LSG self noise from its own electronics.

506

Implementation of a volume-filling cell arrangement, presents significant engineering challenges beyond those encountered for the two-cell arrangement in the P-2000. Layout of the optical pathways, which channel the laser light beam to four mutually orthogonal cells, requires added technical skill as compared to the task for two cells in the P-2000. A tetrahedron represents one natural geometry for volume filling. Unfortunately, a tetrahedral arrangement is currently not feasible for the 12-3/4" UUVs for the following reason. Each cell is surrounded by a coil used to drive a magnetic resonance field in the cell's gas. The coil-generated fields from one coil will generate cross talk in the adjacent cells. As a consequence, the cell-to-cell separations must be large enough so that the cross talk between the cells does not limit sensitivity. An effort has been pursued to reduce intra-cell cross talk by reducing the diameter of these coils from 3" down to 2". This has permitted the reduction in cell-to-cell separation from 12.0" down to 9.5" without loss of sensitivity. Unfortunately, that separation is insufficient to permit form fitting of a tetrahedron into a 12-3/4" body section. Hence a less natural staggered volume-filling arrangement has been introduced. The reduced cell-to-cell separation does offer one significant benefit: the four-cell cluster in this staggered configuration has a length of 15", 11" shorter than the original design [20].

A design of the LSG electronics subsystem conceptually similar to the P-2000 has been pursued. However, the size and power requirements for operation in a 12-3/4" UUV and the requirement for autonomous sensor operation present very difficult engineering challenges. Conversion from a design based on a mixture of discrete analog and digital circuits partitioned in 3 separate units to integrated digital surface mount technology and integration of all of the system resonance loop electronics into the sensor unit were pursued to meet these requirements. Introduction of pizeo-electric

devices to ignite and sustain the excited state of the helium gas has eliminated the space and power of the conventional high voltage rf power supply that was used for excitation in the P-2000. A factor of 30 reduction in power consumption over the current P-2000 has been realized. A computer and signal-digitization circuitry have also been integrated into the electronics subsystem to provide autonomous sensor control, data storage, and real-time signal processing [20].

This sensor is currently being manufactured for delivery in 2004. Algorithms developed previously for five-channel tensor gradiometers are currently being tailored for use with these four-channel scalar gradiometer/magnetometers. Underwater sensor testing onboard a UUV is planned in 2004-2005.

D. Active EM Sensing for Buried Minehunting

Active EM sensors, which incorporate a magnetic-field coil receiver and a magnetic-field coil transmitter, have been effectively demonstrated for eddy-current detection of the metallic components in land mines and unexploded ordnance (UXO) buried on land. The Geophex GEM-3 is one such sensor [21]-[22] displayed for underwater application in Fig. 15. It transmits broadband signals that will excite the broadband EM emission spectrum of a target. New discrimination signal processing, known as Electromagnetic Induction Spectroscopy (EMIS), has been developed to classify a target by matching the observed spectrum with the spectra of known mine targets. Broadband, multi-spectral sensors can provide more information than passive magnetic sensors, such as the ones described in Sections IV.B and IV.C, which measure, at most, the three components of the target's magnetic moment vector.

(a)

(b)

Figure 15. GEM-3 tow system demonstrated for UXO test conducted at Mare Island in 1999: (a) display of sensor subsystem with two GEM-3 units mounted on either side of cross beam support on small towed craft and (b) view of tow system deployed in the water.

Active EM sensors modeled after the GEM-3 or comparable sensor types are being explored for application to underwater buried mine detection. There are several key factors that impact the operation of active EM sensors in this setting. First, active EM sensors used for the detection of mines and UXO on land are typically operated in close proximity to a target. In contrast, for the concepts being explored under the BMH project, the active EM sensor will be operated onboard a UUV flying at a height on the order of 3 meters above the sea floor. This means that the sensor must detect and classify targets at a relatively long range by the standards for land mine detection. On the other hand, the targets of interest for the underwater case have a much higher metallic content than plastic mines commonly used on land. Operation in sea water introduces a new factor: the salt content of sea water gives this medium a relatively high conductivity compared to air, drier soils away from beaches, and fresh water. As a consequence, the EM waves generated by an active EM sensor will be more highly attenuated when propagating through sea water than when propagating through air or fresh water.

A prototype GEM-3 system was successfully demonstrated to detect buried UXO at an underwater UXO test site near Mare Island in San Francisco Bay in 1999 (Fig. 15). During the tests, targets were detected at ranges significantly greater than expected. A new hypothesis to explain the anomalous results of these tests was established from theoretical investigations conducted after the testing [21]. The eddy-current response mechanism describing active EM detection of metallic targets on land has generally been accepted as the primary mechanism for the sea-water case; i.e. EM waves projected by the sensor transmitter excite eddy currents in metallic components in the target and the eddy currents, in turn, generate secondary EM waves that can be detected by the sensor's receiver. Unlike the case on land or in fresh water, the source magnetic fields propagating through salt water will generate electrical currents in the conductive salt water. At a target, these currents will channel around the target. This perturbation will, in turn, excite secondary electric currents characteristic of the target that can be detected by the receiver. Based on this interpretation, the new target response has been labeled as the current-channel response (CCR) in contrast to the better known eddy-current response (ECR). At low frequencies, the CCR signal detected at the receiver displays an inverse fourth-power dependence on range to target, which contrasts to an inverse sixth-power dependence on range to target for ECR. Hence CCR will be stronger than ECR under certain conditions [21]. Several independent analytical models, which have been independently developed to describe the scattering of magnetic dipole fields from spheres in a conducting medium, are currently being exercised to better understand and exploit the two mechanisms.

Analysis for active EM detection has primarily been limited to solid and shell targets with spherical shapes. The spheroidal T-matrix formalism for acoustic scattering has been developed to describe acoustic scattering from elongated shapes in water [23]. This model is currently being adapted to describe EM scattering in seawater for elongated shapes [24]. This adaptation is not straightforward, but appears to be feasible. It will ultimately provide a capability to assess the importance of target shape to active electromagnetic sensing in the underwater environment.

The preceding discussion has been focused on targets suspended in the water column. Those investigations fail to take into account the impact of EM wave scattering at the bottom interface and wave propagation into the sea floor for the case in which the target is buried. To address this problem, a model has been developed to describe both the scattering from a dipole sphere and from the water-bottom interface. This model is exact. In particular, it accounts for both eddy-current and current-channeling responses. Analysis conducted using this model indicates that the sea floor will reflect a substantial percentage of the EM energy in cases where the bottom displays a high conductivity contrast [25].

The preceding theoretical development is idealized in the following sense: (1) the sensor is moving in level flight at constant speed through the water, (2) the water and sediment are homogenous, (3) the sea floor interface is flat, and (4) the air-water interface can be ignored. As a consequence of the analysis in [25], the return signals from EM waves scattered off the sea bottom can be much greater in strength than the corresponding return signals from the target. Then, if the strength of signals scattered off the ocean floor fluctuates, it will be difficult to discriminate the small target signals. Moreover, large fluctuations in the bottom-scattered signals are expected once platform rotation in UUV flight, inhomogeneity in sediment conductivity, and roughness of the sea floor interface are accounted for in the analysis. Several studies are in progress to examine performance limitations due to such environmental factors [26]-[27].

Physics-based sensor fusion approaches are being investigated to compensate for noise in active EM sensors that arise from vehicle rotation, bottom inhomogeneity, and interface roughness. In particular, an approach is being explored to co-locate BOSS with an active EM sensor and then use BOSS data to compensate for these noises in addition to more straightforward application of the sensor fusion combination for target classification and clutter rejection [26].

A comprehensive perspective for active EM detection of buried targets in sea water, encompassing all of the phenomena described above, remains to be fully established. Experimentation will play a very important role to validate the models and determine the relative importance of the various factors already identified and others that may be identified through further investigation. Controlled experiments to assess sensor performance and to validate/refine the models will be initiated in 2004 using an underwater rail structure constructed to hold and guide the GEM-3 sensor assembly for controlled experiments. Measurements will be conducted using model metallic, ferrous, and dielectric validation targets with the targets positioned in air, in seawater, and fully buried in sediment. In addition, experiments to quantify the impact of UUV

conductivity/magnetic signature and electrically generated noise on GEM-3 performance will be conducted in a manner similar to those conducted for passive magnetic sensors. Following this preliminary sensor experimentation, an advanced active EM sensor dedicated for operation onboard the 12-3/4" UUVs will be developed and tested first on a rail and subsequently onboard a 12-3/4" UUV.

E. Optical-Quality Imaging of Partially Buried Mines

High-performance electro-optic identification (EOID) sensors, e.g. the Streak Tube Imaging Lidar [28], are now entering the fleet for reacquisition and identification of proud targets that have been classified as mines previously in an initial SCM operational phase. These EO sensors can produce clear high-resolution images of proud bottom targets at reasonable standoff distances through moderately turbid waters. Nevertheless, buried and partially buried mines remain problematic. In particular, the EO sensors are unable to image a fully buried mine below the sea bottom.

However these sensors may be used to enhance classification once they are incorporated into a sensor-fusion approach [29]. First, they can image the scar of a target fully buried in the bottom, even if they cannot image what is underneath; e.g. the EO image shown in Fig. 16. While not satisfactory for identification in the currently accepted sense, this cue would obviously provide added confidence that the contact was a mine.

For some missions the majority of mines will only be partially buried. In such cases, EO sensors will be able to image the exposed portion of the contact as shown in Fig. 17. Depending on the percent and orientation of the exposed object, the probability of classification obtained in a fusion approach with other sensors will increase. If the majority of the object is proud within a scour pit, a skilled operator may

even be able to identify a mine from its EO reflectance imagery. In case the contrast levels from reflectance imagery of partially buried targets is not adequate to clearly define the shape of partially buried objects, range imagery from a 3-D imaging system can potentially be used to determine the geometry of unburied portions of the target.

The EOID sensors entering the fleet for operation in towed systems are considered too large and costly to deploy on small UUVs. Several comparable EO approaches capable of operation onboard the 12-3/4" UUVs have been proposed. Two interesting options are the Underwater Scannerless Range Imager (USRI) and the Jigsaw Multi-Aspect LADAR (MAL). The USRI is a 3-D imaging system that employs a modulated source and a modulated gain stage in the receiver (image intensifier) [30]-[32]. A phase image results from mixing of the backscattered return illumination from the target with the modulated gain of the image intensifier. Then a range image is constructed from a sequence of phase images. The Jigsaw MAL is designed to interrogate targets and its context from a host of diverse look angles. Sophisticated classification algorithms are implemented to remove LADAR returns from the surrounding clutter so that only the target remains in the resulting 3D visualization product [33].

High-resolution acoustic sonars operating at frequencies greater than common for conventional sonars (typically 600 kHz or less) can provide detailed shape and texture discrimination than is obtained from conventional sonars. In fact, this discrimination approaches that possible with EO sensors. These sonars can be used to image partially buried mines in a manner similar to that described above for the EO sensors, although they will lack some optical cues such as color discrimination possibly obtained by optical reflectance imagery.

Fig. 16. EO image of scar from a fully buried target.

Fig. 17. EO reflectance image of exposed portion of a partially buried target.

The Dual-Frequency Identification Sonar (DIDSON) is one such sonar [34]. It provides a 29° field of view while operating at 1.8 MHz or 1.0 MHz. At 1.8 MHz, it has a horizontal resolution of 0.3° and can image out to ranges of about 15 m. At 1.0 MHz, DIDSON's horizontal resolution is lower, with a value of 0.6°, but it can image at ranges approaching 40 m. One version of DIDSON will be integrated into a Bluefin12 UUV. Plans are under consideration to evaluate this sensor against partially buried mines in various BMH sensor-fusion concepts.

V. SUMMARY AND FUTURE PLANS

The current focus of the BMH Project is the development and testing of individual sensors. The sensors described in Sections III and IV are currently in various stages of development. Development and initial testing of capable versions of most of these candidate sensor types is expected by the end of 2004. Sensor performance models are being developed or enhanced to address the issues arising from target burial and from operations onboard UUVs. Affiliated signal and image processing is being developed to support these sensor developments. There is now a focus in sensor design for integration into the new 12-3/4" UUVs currently being developed for ONR. In this list, we include the SSAM, the BOSS, the RTG, and the LSG. The two primary exceptions are the existing versions of the BBSAS and the VLF Acoustic-Color Classifier that have been developed for the existing 21" Reliant. Active EM for this application is in an early stage of development. Dedicated research in this area, including controlled experiments, is being initiated. The value of other sensor types for this application, such as EO sensors, especially in sensor-fusion approaches continues to be evaluated.

Preliminary tests to evaluate existing prototypes of some of the principal sensor types are being conducted in the near term. In these tests, the prototypes are being deployed onboard various platforms of opportunity for independent tests conducted sequentially against common target fields. Although project status does not permit optimal configuration of the ultimate sensor suites in final vehicles, this testing will give us a first look at the overall effectiveness of the sensors being evaluated. The individual tests are being conducted in a short time period to reduce any variability in mine burial and other environmental conditions.

Emphasis will move in 2005 to develop and evaluate optimized sensor fusion approaches for search and reacquisition. Data fusion algorithm development will be aggressively pursued and dedicated system prototypes with optimized sensor suites will be assembled. The integrated systems will be evaluated in the period of 2005-2007. A final demonstration of the system prototypes in coordinated operations is planned for Kernel Blitz'07.

Acknowledgements

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